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The High Resolution Imaging (HRI) portable array, a seismic (and internet) network dedicated to kilometric scale seismic imaging

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Abstract

We have developed a network of portable seismic stations dedicated to the high resolution imaging of geological, potentially hazardous, targets. These targets - volcanoes, fault zones, landslide areas - are characterized by strong medium heterogeneities, rugged topography, rough field conditions, and require dedicated equipment in order to maximize the number of recording points. This new network is designed to a) operate experiments with a limited size crew, b) run on low power for possible use in remote areas and difficult conditions, c) record both active and passive seismic sources. The actual network consists of 30 clusters of 9 channels digital acquisition system (DAS), equipped with 6 vertical sensors plus 1 three-component sensor and one cluster of 24 vertical sensors. Each DAS uses Ethernet and 802.11 (WiFi) connections that permit to a single operator to remotely control the entire network. We present the main characteristics of this new portable array, describe the calibration method developed for our sensors and show examples of configuration and recordings for two recent experiments.

Introduction

The geophysical characterization of geological structures remains a major task in natural hazard mitigation. Questions regarding the dynamics of physical processes related to

natural hazards (e.g. landslides, seismic or volcanic hazards) often require to constrain the geometry and the spatial distribution of some physical parameters, or to map the location of temporal changes in the structures. To address these problems: mapping an object geometry (e.g. fault gouge), a surface of physical discontinuity (e.g. water circulation, sliding surface), a spatial and temporal distribution of physical properties (e.g. feeder conduits), a “high resolution” probing tool is needed. Although the “high resolution” term may be used by many people for very different imaging scales (from subsurface **shallow** imaging to 3D oil exploration imaging, for instance), it has a common experimental implication: high resolution imaging implies a high density of measurement points. A large effort has been made these last twenty years to develop portable networks throughout the world and increase the number of available seismographs. The IRIS PASSCAL program (US, Fowler and Pavlis, 1994)) for instance provides a pool of over 1000 portable seismographs. The GIPP (Geophysical Instrument Pool at Potsdam) at GFZ (Germany) is yet another important initiative offering several hundreds of seismographs. Since we cannot be exhaustive, we just emphasize that while many networks are devoted to crustal or lithospheric studies, others also offer equipment to perform shallower imaging (e.g. SEIS-UK in the UK, A., Horleston, A. and Denton, (2004), or PASSCAL/**single channel Texans recorders**), or volcanic imaging (Morita and Hamaguchi, 1996).

This paper provides a technical overview of the High Resolution Imaging (HRI) array of portable seismic stations with an emphasis on its communication capabilities. This tool that has been designed to provide a flexible and efficient instrument in 3D seismic imaging experiments conducted on targets with a typical size from several hundred meters to a few kilometers.

The HRI project

The goal of the HRI project is to perform 3D imaging of geological targets that are potentially hazardous: fault zones, volcanic areas, landslides areas, etc... An overview of the areas of interest, such as the Soufrière volcano of Guadeloupe (Lesser Antilles), showed us that the most common scales of investigation are comprised between several hundred meters and a few kilometers. In the standard of academic experiments, these scales are smaller than those of crustal investigations and larger than the size of shallow geophysical exploration. Given these objectives, the desired seismic tool has to satisfy the following constraints:

- a) Ability to operate experiments with a limited size crew
- b) Low power consumption for possible use in remote areas and rough conditions
- c) Capacity to record both active and passive seismic sources

These constraints are partially satisfied by i) **exploration** or by ii) seismological equipments:

i) 24 to 64 channels seismic acquisition systems offer a very efficient real time quality control and can be operated by a limited number of people in the field, however they suffer from a high power consumption (>10 W). ii) Standalone seismological digital acquisition systems (DAS) with 3 to 6 channels, with or without integrated sensor, have low power consumption (usually below 1 W) but they do not easily allow a real time quality control when recording active seismic sources.

For these reasons, we decided to develop a new type of equipment whose technical characteristics offer a trade-off between seismological and seismic solutions: 3 to 24 channel acquisition systems, low-power (1.2 W for 9 channels at 500 Hz, see table 1), equipped with internet communications (Ethernet, 802.11, WiFi radio, PPP over serial) to allow real time and remote control of operations and local storage of data. Another choice regards the optimal number of channels per datalogger. This again is a trade-off between the number of dataloggers and the total length of cable to be deployed to connect the sensors. This is an

important issue in rough field conditions like volcanoes where deploying long cables can become problematic. The solution that we kept is based on clusters of 9 channels DAS (Fig. 2) equipped with 6 vertical sensors and 1 three component sensor, plus one additional 24 channels DAS that can be deployed with either, 8 three component sensors, 24 standalone vertical sensors or two cables of 12 seismic geophones. Finally, the actual HRI network consists of thirty 9-channels clusters, one 24-channels cluster, and an additional 24-channels Geode (Geometrics) acquisition system that is used to control active source such as vibrator trucks.

DAS and sensor design

The digital acquisition systems and the sensors were developed jointly by university laboratories (Universities of Grenoble, Toulouse and Nice) and the French Agecodagis SARL company. The DAS is made up of two electronic boards: the digitizer board is based on commercial 24-bit digitizer chips ($\Sigma\Delta$ modulation) and is designed for 3 to 24 channels; it is interfaced with a ARM (low power), 32-bit (Linux compatible), processor board. The first board contains the digitizer and the clock (TCXO). Its job is to digitize the electrical data signals, time-stamp them, and perform some triggering tests. The processor board receives the data in raw format and its role is to compress, to format and to store the data on storage media. This board runs a Linux operating system, which is an advantage because this system is widely used in the academic community and anyone with a good background in Unix programming can develop and test his own program utilities. The board is equipped with several standard I/O interfaces, in particular a 10Mbyte Ethernet port (100Mbyte for newer versions), two serial ports and two pc-card slots. One slot is used for data storage and, in the HRI present version, the second slot is used with an 802.11b “WiFi” 100 mW radio card connected to an external antenna. The DAS offers a choice of sampling rates from 1 Hz to 2-

kHz. It must be noted that this is less than the 30kHz sampling rate found on most 24-64 channels geophysical acquisition equipment. This DAS offers a variety of acquisition modes in order to record either passive or active seismic sources. It can record data in continuous mode or in triggered modes where trigger signals are either software triggers (data threshold, operator decision, time window) or hardware triggers (external electrical signal). The DAS operates with an external GPS that synchronizes an internal clock which runs on its own internal battery with a 1 μ sec timing accuracy. This particular hardware design permits to keep a good timing precision in the case where stations have to be installed for a short period of time, in places where no GPS satellites are in view.

The 1- and 3-component seismometers have been partly developed for this project. They both include standard 2 Hz single coil geophones and an amplifier board including a special calibration circuit. The signal is amplified within the sensor case and no amplification is needed at the DAS input. This hardware setting permits to extend the working frequency band down to 0.2 Hz. Below 0.2Hz, the standard seismic noise level reaches the digitizer input noise in normal conditions (see figure 3). To use the full frequency band requires performing a correct instrumental response with accuracy better than a few percent. Since the geophones do not present a stability as good as, e.g., broadband sensors, we must be able to measure easily and in the field the sensor parameters (gain, free period, damping factor). This is achieved through a circuit located on the amplifier board. It receives a periodic signal from the DAS on dedicated wires, and converts it into a succession of steps with variable length, a binary like signals (Figure 2) with typical length of 60sec whose signature is different for every sensor. This signal is sent to the sensor signal coil and the response is recorded by the DAS. The calibration procedure is detailed in appendix A. The sensor identification allows us to associate, afterwards, a sensor to a channel-DAS couple and to track more easily malfunctioning sensors. Figure 3 shows the comparison between sensors responses computed

with the above method, and the spectral ratio computed between a STS2 broadband sensor and two geophones (1 HRI vertical sensors and a 1Hz L4C Mark Product). The response to the excitation signals are fitted with absolute errors smaller than 2%, while the modeled sensor velocity response fit the spectral ratio shape between 0.2 and 10Hz with errors of about 5%.

We have conducted so far active seismic experiments with short periods of recording (typically few weeks). In these conditions, the calibration procedure is used to correct for sensor response perturbations due to vertical misalignments, or damaged instruments. The corrections are performed only once, when processing the data. Another philosophy that is not yet implement in the DAS, would be to calculate on board, and apply in real-time the filter coefficients that correct for the instrument response. This would be of great interest for long recording periods where the sensors may deviate from their initial response during the course of the experiment.

Communications within the HRI seismic network

While the HRI digitizer characteristics are close to those found on most equipment, the main HRI network originality lies in the communication capabilities that come with the simultaneous use of wired and wireless internet connections. The network is able to automatically and dynamically configure (or route) itself through different hardware links (wired ethernet or PPP, wireless Wifi). From the user point of view, this means that once the seismic network is set with a configuration that satisfies the scientific objectives (1D lines, 2D grids, 2D clusters, etc...), the network uses all existing links to present itself as a homogenous group of internet nodes, clearly identified by virtual and fixed identifiers.

Technically, each DAS acts as a network router and runs a dynamic routing algorithm that is able to find the best way to reach other nodes either using Ethernet, PPP or Wifi (radio)

links. Radio links use the 802.11b standard (1 to 11 Mbs) in the so-called “Ad-Hoc” mode. The Ad-Hoc mode is one of the two modes that are available when configuring a Wifi network. On the other hand, the “infrastructure” mode is the most commonly used but is not well adapted to outdoor use since it requires a central or “access” point to distribute all communications. The Ad-Hoc mode (MANET, 1999) is a point-to-point protocol where all nodes play the same role and can talk to each other. This mode is more flexible and well adapted to configurations where obstacles prevent to set “central points” . A drawback of the “Ad-Hoc” mode is that the real data throughput is often less than that of the “infrastructure” mode. In practical, in order to optimize communications, we have also developed outdoor Ethernet hubs and radio relays in order to deploy network nodes in places where no DASes are needed. The radio relay can also be used as a distant radio connected to a DAS by an Ethernet cable (180 m) for cases where DASes are settled in radio shadow zones. These outdoor gears can receive power either directly from batteries or through the Ethernet cables.

The radio frequency that is used (2.4 GHz) and the low power (100 mW) emitters limit the radio link quality. The best quality is thus obtained with the lowest radio data speed (1 or 2 Mbps). Trees, bushes, radio interferences as well as rain fall can strongly affect radio transmissions. To circumvent these limitations, we use specific antenna for different situations (patch, omni-directional, mounted on mast). The overall data throughput is of the order of 30kbyte/s. Communications are then limited to real time control and data checking, and do not allow real time data transfer. Finally, while communications facilitate the seismic network management, one cannot neglect the time needed to deploy an efficient radio+Ethernet network. Thus, HRI network installation really consists of two different steps: setting up a seismic network and setting up a communication network.

Managing the seismic network is performed through web interfaces. Finally, the DASes can be programmed individually (site name ...) or globally (trigger conditions, idle or wakeup time) depending on the chosen parameters.

Two test cases, the “Puy des Goules” and “Soufrière de Guadeloupe” experiments

The first experiment using the entire network took place for one month in November 2004 on a small volcano located in the “Chaîne des Puys” in central France (Brenguier et al., 2006). This volcano is a Strombolian cone that had a single eruption about 15000 years ago. Besides testing the HRI equipment, the goal of this experiment was to study the base of the cone and to obtain the velocity structure of a zone containing feeder conduits located below several hundred meters of scoria. Active sources, (explosives and vibrator) were used at about 900 points and were recorded by 210 to 248 geophones. Fig. 4 shows the detail of the internet network configuration. The network was managed from two different node location (three being available). From these points, an in depth control of the 30 stations with full parameter checking took about 1.5 hour, i.e. ~15mn per DAS. The stations were configured to save power and forced to sleep mode during active-source idle time: from 8 am to 8 pm when the vibrator was running at night, from 6 pm to 8 am when shooting explosive sources.

The second experiment took place in February 2006 on the *Soufrière de Guadeloupe* volcano in Lesser Antilles. Several 2D profiles were successively deployed on the summit to record dynamite shots across the dome in order to characterize its structure. The network topology for the longest profile is shown on Fig. 6, and **is comprised of radio and wire links. Ethernet (wire) links are chosen and set at installation time as an alternative to radio relay when two consecutive nodes are close, but not in view of each other. Once the seismic network is set, the communication network self-organizes to offer the best route going from one node to the others.** During this experiment, the internet network was used to control the

stations and to retrieve daily the shot records (ex. Figure 7) from the permanent *Soufrière* Observatory, distant of 8km. The dome elevation is 1400m, and it is under the effects of strong winds and extremely heavy rain falls. Remote operations considerably help the people to manage the equipment that was visited only when needed. Finally, we also used the remote real time control to measure the noise level on the stations located on the windward side and to trigger the shots in the best wind conditions.

Conclusion

The HRI network of portable seismic stations and sensors was developed to meet a wide range of seismic imaging applications, using passive or active seismic sources, for scales of investigation varying from 100 m to a few kilometers. Its specific design based on clusters of seven sensors suits various experimental configurations: from 2D or 3D seismic investigations on rough topography area to wave field analysis with seismic antennas (Cornou et al., 2003). The next objective is now to develop specific methods to analyze the data recorded by the network. A special effort is needed to take into account strong velocity contrasts or topography like those present in volcanic areas, or fault zones like Anatolian fault near Izmit (e.g. Dietrich et al., 2004)

Acknowledgment

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Table 1: HRI stations power consumption in field conditions

- DAS + sensors + gps + 100mW radio - 9 channels@500Hz continuous recording on hard disk	no duty cycle	GPS duty cycle (5mn/hr) Radio duty cycle (12hr/day)	GPS duty cycle (5mn/hr) DAS+Radio duty cycle (12hr/day)
	4.3W	2.5W	1.2 W
	100mW radio	Sensors (one 3C, six 1C)	DAS alone, 9 channels@1kHz
Continuous power consumption	1.5 W	0.5W	1 W

Figure captions

Figure 1: A 9 channels HRI cluster consists of a DAS (black box at center), 6 vertical seismometers (back), 1 three-components seismometer (at front), a radio antenna (white stick). It is powered by a 60AH battery (right) and a solar panel (left). A 24 channels cluster would be identical, but uses two 12 channels connectors that can be split further by breakout boxes.

Figure 2: Example of 42 sec of calibration signal recorded on a HRI sensor in a noisy environment. Embedded plot shows the complete calibration sequence. Notice the different step lengths that determine a binary code unique for each sensor. The main plot shows the average excitation for down going steps (black) and the modeled response (red), the relative rms is 0.8%.

Figure 3: Comparison between two sensor responses (1Hz L4C and 2Hz HRI) modeled by the calibration method (in green), and the spectral ratios computed between the sensors and a Streckeisen STS2 reference seismometer on a 8 hours noise record. Notice that the 2Hz HRI sensors record the ground noise down to 0.2Hz

Figure 4: Internet network deployment on the “Puy des Goules” experiment. Yellow dots denote DAS location (25 visible for a total of 30); white lines, radio links; red lines, Ethernet (wire) links. The Puy des Goules volcano is 900m in diameter and 250m high.

Figure 5: Internet network configuration for the “Soufrière de Guadeloupe” summit dome experiment. White lines denote radio links; red lines, Ethernet (wire) links. The seismic network was managed from the OVSG Observatory, 8 km away using another radio relay. The red stars show the shot locations

Figure 6: Example of a seismic profile recorded by HRI network across the dome of the “Soufrière de Guadeloupe”. Sensors were deployed every 10m. Two P-wave arrivals can be identified, the first is weak, the second comes about 100ms later. Note the effect of the dome-crater contact at 250m. Surface or trapped waves can be observed later with diffraction at 620m due to the *piton Dolomieu*.



Figure 1

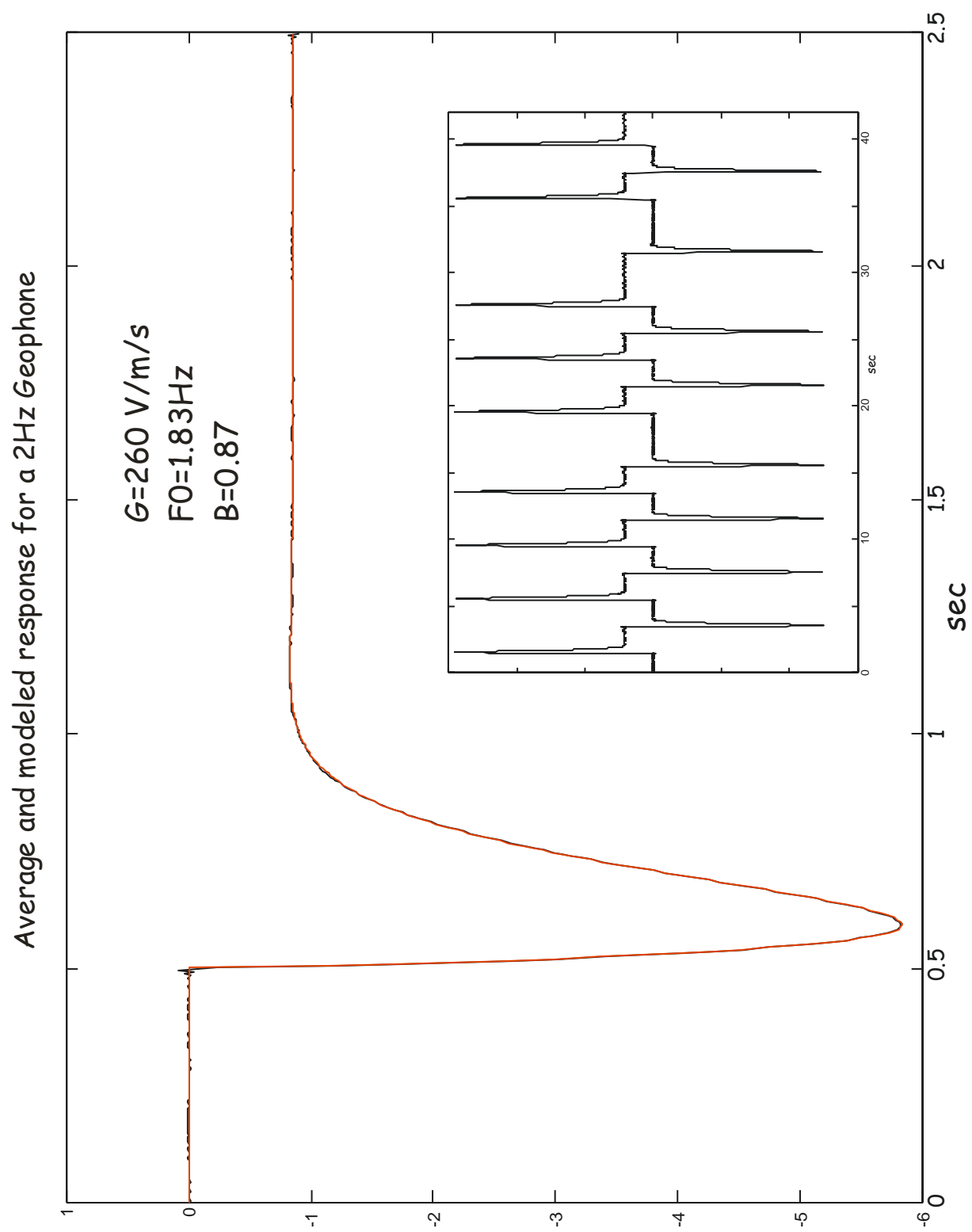


Figure 2

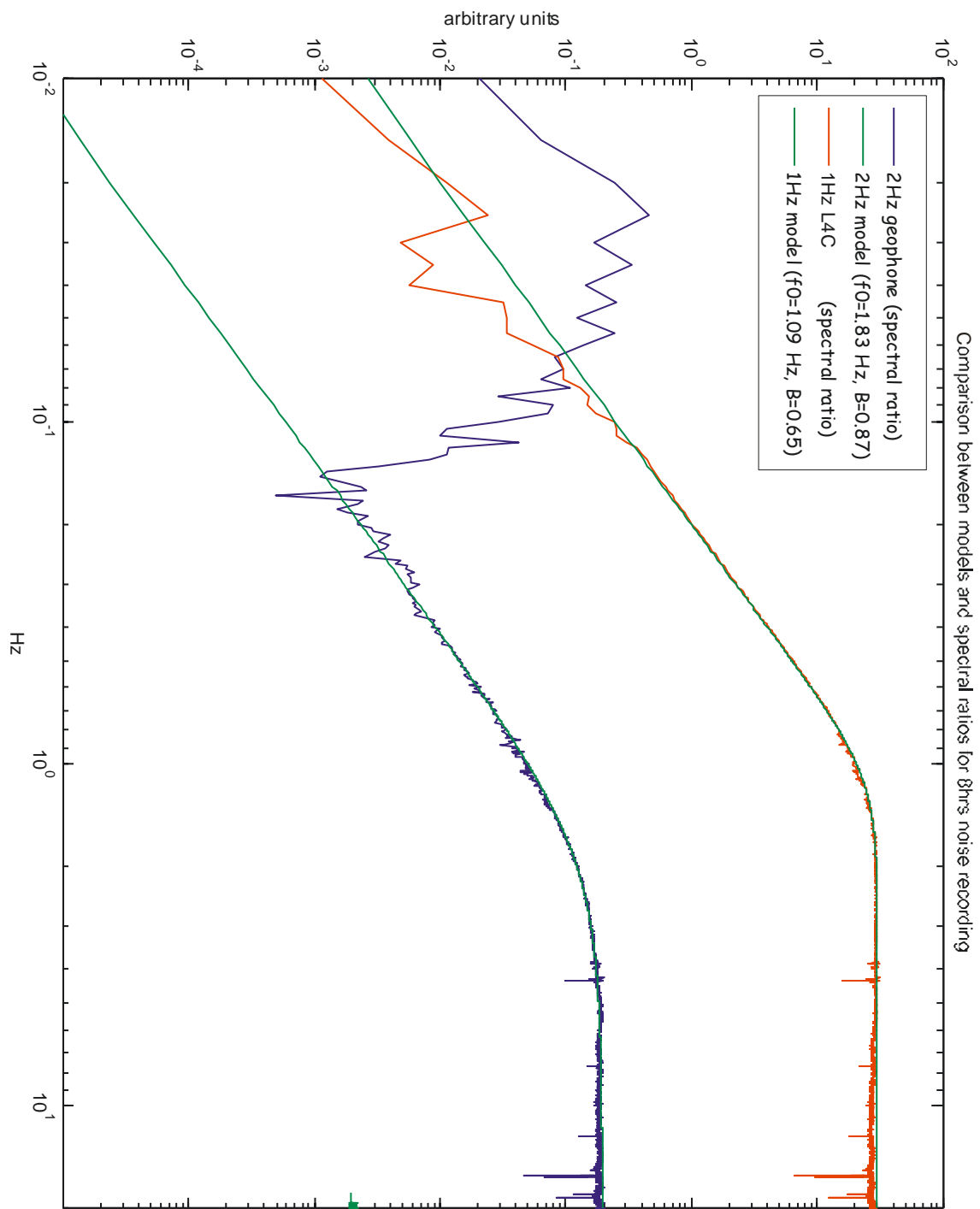


Figure 3

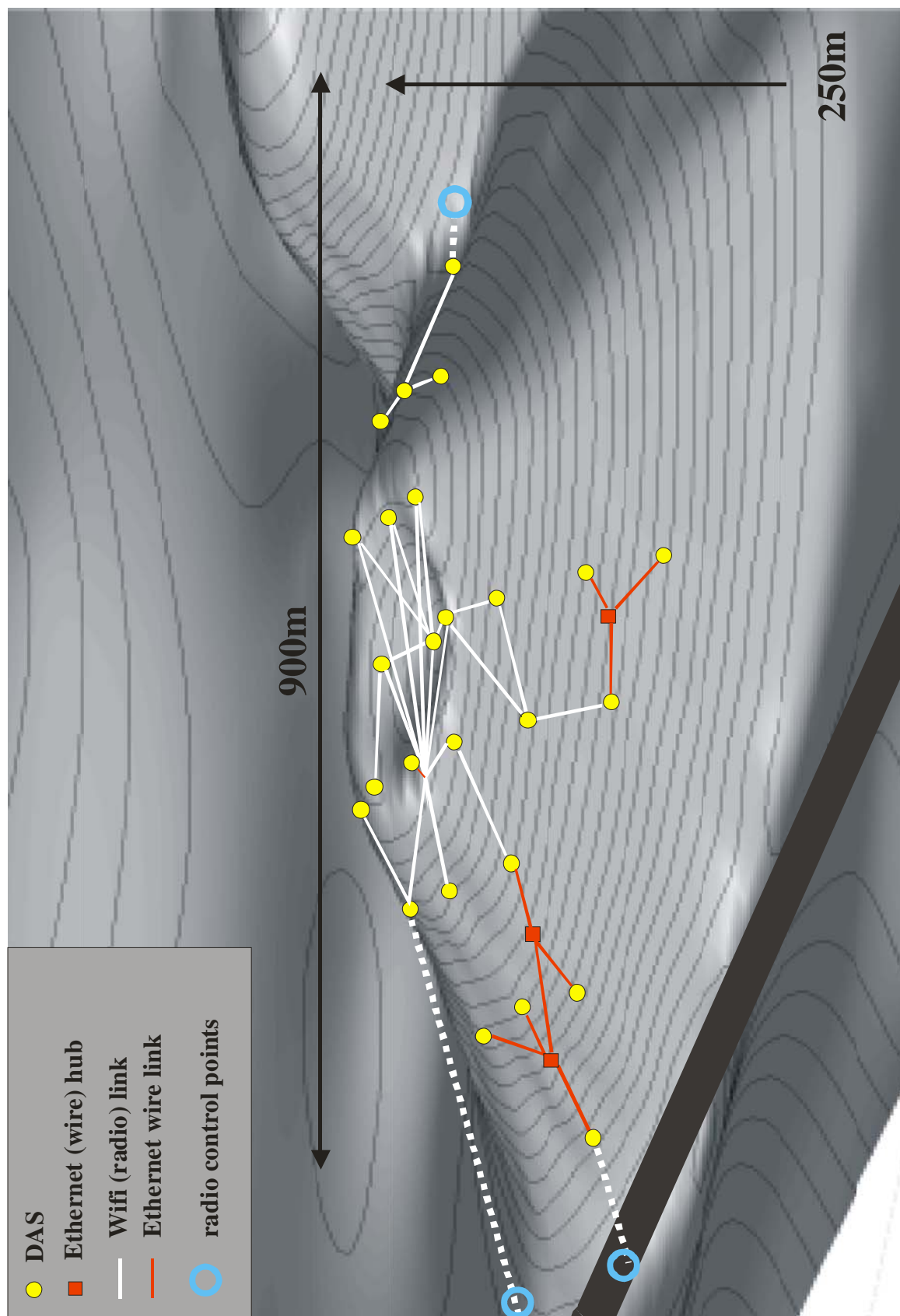


Figure 4

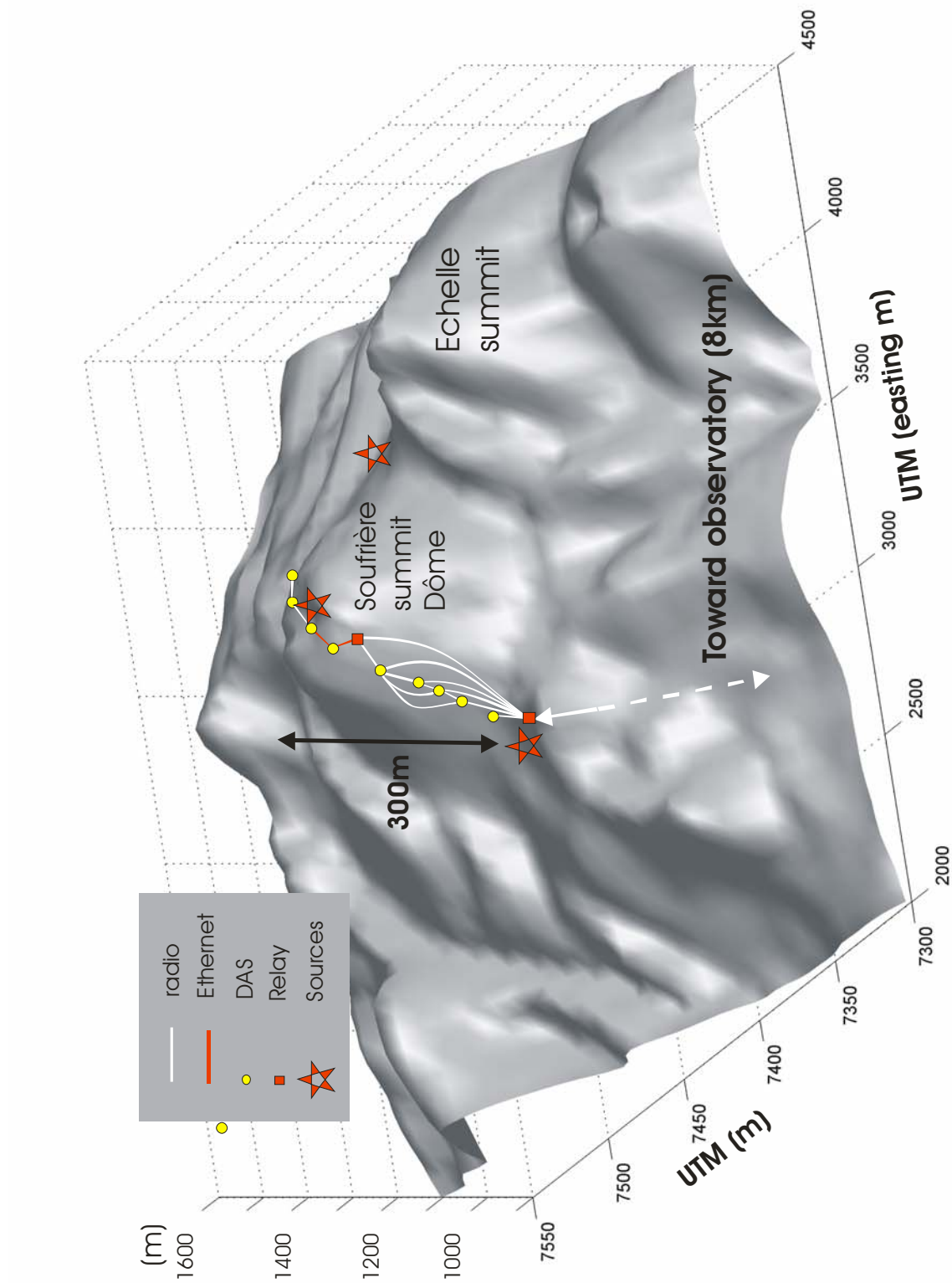


Figure 5

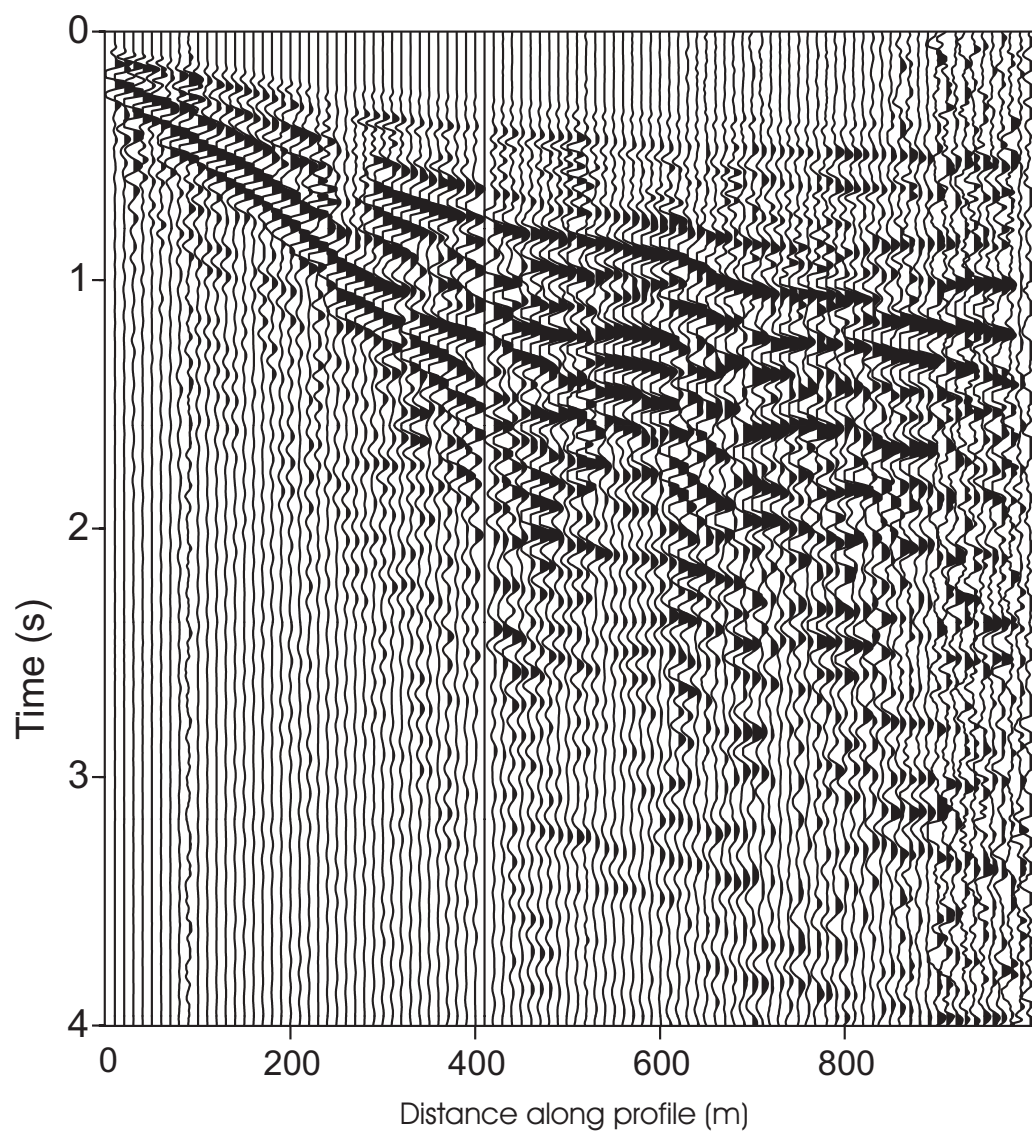
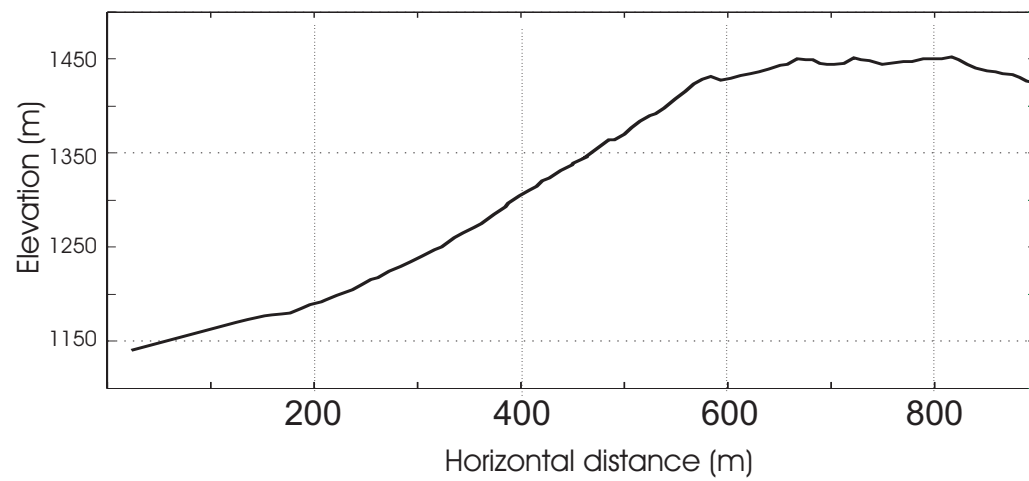


Figure 6

Appendix A

To keep a short demonstration, we use in the following the same notations as Rodgers et al (1995) referred below as R95. The Laplace transfer function for the electromagnetic seismometer giving the output voltage with respect to ground velocity is (eq. 5 of R95):

$$VS(s) = \frac{E(s)_{out}}{\dot{X}(s)} = \frac{G_d s^2}{s^2 + 2\zeta\Omega s + \Omega^2} \text{ [Volt/ms}^{-1}\text{]}.$$

We now consider the output voltage generated by an external acceleration $\Gamma(s)$ applied to the moving mass M . Using the same equation of motion, the Laplace transfer function writes:

$$\frac{E(s)_{out}}{\Gamma(s) + \ddot{X}(s)} = \frac{G_d s}{s^2 + 2\zeta\Omega s + \Omega^2}. \quad \Gamma(s) \text{ is generated by a voltage step } U \text{ applied to the sensor output.}$$

It creates a force on the coil: $F = G_{sig} \frac{U}{r_c}$ (r_c is the signal coil resistance) and hence, an

$$\text{acceleration } \Gamma = \frac{G_{sig} U}{Mr_c} \text{ (see R95 for details).}$$

The overall response of the seismometer to a voltage step $\frac{U}{s}$ applied on its output can thus be written as:

$$C(s) = \frac{U}{s} + \frac{G_{sig} U}{Mr_c} \frac{G_d}{s^2 + 2\zeta\Omega s + \Omega^2} = \frac{U}{s} \left(\frac{s^2 + (2\zeta\Omega + K)s + \Omega^2}{s^2 + 2\zeta\Omega s + \Omega^2} \right) \quad (1)$$

where $K = \frac{G_d G_{sig}}{Mr_c}$ and where we assume $\ddot{X}(s) \ll \Gamma(s)$ ($\ddot{X}(s)$: ground noise acceleration).

The calibration signal that is sent to the signal coil (Figure 2) is a succession of steps having same amplitude, but opposite signs. It is then described by equation 1. Assuming that the voltage step is either known or measured on the digital records, we wish to determine the three parameters (Ω, ζ, K) and hence, the sensor parameters (Ω, ζ, G_d) since K may be rewritten

as $K = \frac{G_d^2}{M.R}$ (see R95) where $R = \frac{r_c r_d}{r_c + r_d}$ is the total sensor resistance.

In order to determine (Ω, ζ, K) , we use a parametric modeling as follow. A digital system (Z-transform) analog, but not equal, to Laplace transfer function (1) can be derived using for instance the integration analog model or bilinear method (see e.g Kunt, 1984, Parks & Burrus, 1987). In this method, the Z-transform analog to (1) is obtained by replacing Laplace variable s ,

by the expression $s \rightarrow \frac{2}{\Delta t} \frac{1 - z^{-1}}{1 + z^{-1}} = 2fs \frac{z - 1}{z + 1}$ where fs is the sampling frequency used when digitizing the signals.

The Z-transform that describes the digital system equivalent to (1) writes:

$$C(z) = \frac{S(z)}{E_{excit}(z)} = \frac{1 + C + B.z^{-1} + (A - C).z^{-2}}{1 + B.z^{-1} + A.z^{-2}} \quad (2) \quad \text{where } (A, B, C) \text{ depend upon } (\Omega, \zeta, K, fs)$$

$S(z)$ represents the digitized calibration signal, and $E_{excit}(z)$ represents the excitation signal sent to the signal coil. In the same way, we obtain from Eq. 5 of R95, the Z-transform that describes the sensor voltage response to ground velocity, with the same coefficients (A,B,C):

$$\frac{E(z)_{out}}{\dot{X}(z)} = 2f_s C \frac{1 - 2.z^{-1} + z^{-2}}{1 + B.z^{-1} + A.z^{-2}} \quad (3)$$

The complete procedure consists in recording several consecutive steps applied to the sensor signal coils. First, the excitation signal $E_{excit}(t)$ is modeled assuming constant voltage value U , but variable step lengths. For HRI sensors, these different lengths produce a binary code that identifies the sensor serial number. The calibration signal $S(t)$ is related to $E_{excit}(t)$ and the coefficients (A,B,C) by the ARMA filter described by the Z-transform in equation 2.

Finally, to compute (A,B,C) from $S(t)$ and $E_{excit}(t)$, we use a non linear inversion that minimize $\|S(t) - \text{ARMA}(E_{excit}(t), A, B, C)\|$ using the downhill simplex method by Nelder and Mead, (1965). Once (A,B,C) are known, we deduce the sensor parameters (Ω, ζ, G_d) and the digital filter coefficients $A(fs)$, $B(fs)$ and $C(fs)$ necessary to model or remove the sensor response on any records.

The main advantage of this method as compared to Rodgers et al. (1995) is the possibility to average the responses for several consecutive steps. This reduces the effect of ground noise acceleration that in turn, reduces the necessary current applied to the coil. We then apply a smaller mass deviation that remains closer to its linear range. In its principle, the method only requires sending a calibration signal to the signal coil, no switch is needed. The determination of the sensor gain requires measuring the total sensor resistance R , instead of the current intensity in Rodgers et al. (1995), and knowing the mass value M , usually available from constructor datasheets.